Corrector Magnet Study for the SNS DTL

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B. Davis
S. Carolina State University

J. Galambos
Oak Ridge National Laboratory

K. Crandall,
TechSource, Albuquerque NM

S. Nath, H. Takeda, J. Stovall
LANL SNS Project, Los Alamos, NM

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Spallation Neutron Source Project
Oak Ridge National laboratory
701 Scarboro Rd. MS 6473
Oak Ridge TN 37830

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Dipole corrector magnets may be useful in the SNS DTL to rectify beam oscillations induced by manufacturing imperfections. In this study we examine the expected magnitude of these oscillations and also study how much of the error induced oscillation can be removed with corrector magnets. We examine the impact on the location and on the number of corrector magnets used. We find that for the nominal magnet error specifications in the SNS DTL, a pair of vertical correctors, a pair of horizontal corrector magnets, and a pair of dual plane BPMs per tank suffice. Use of additional corrector magnets does not further reduce the beam size, but lowers the required average corrector strength. However, if the machine errors are larger than the nominal specifications, use of additional correctors in the first two DTL tanks alleviates excessive corrector strength requirements.

Model / Assumptions

The model used here is the PARTREX code [1]. This model has been used in previous linac corrector studies [2]. The code samples from a user prescribed set of errors and uses a beam envelope model to track the beam oscillations. Corrector strengths are calculated to return the beam on axis at the downstream BPM locations. If more than one corrector pair per plane is used, the corrector strengths are minimized. The maximum beam displacement and fraction of the aperture occupied by the beam are monitored throughout the DTL. The approach used here is to calculate the corrector strengths one tank at a time using BPMs located in the following tank. This approach is adopted since it is likely that the BPMs will possibly not be useful when a tank is active.

The SNS DTL uses a lattice with a FOFO-DODO- pattern, where the "-" represents an empty cell (missing magnet) every third cell. Corrector magnets and BPMs can be placed in these empty cells. Exceptions are that the entrance end wall to each tank is reserved for a current monitor whenever it is empty and the cells in the first half of the first DTL tank are too short to accommodate a corrector magnet. The correctors are electro-magnetic dipoles with a maximum field of 1700 gauss-cm. Errors assumed in this study are shown in Table 1, assuming uniform distributions, with the maximum extent listed in the table. For each case we use 1000 sample sets from the error distributions. For each set of error samples, calculated beam excursion extrema in each tank, as well as the required corrector strengths are stored. Statistical analysis are done on these distributions to estimate the likely-hood of a given beam excursion magnitude. For this study, we concentrate on monitoring three parameters: (1) the maximum beam displacement in a tank, (2) the maximum fraction of the aperture that the beam occupies anywhere within a tank (f_{max}), and (3) the required corrector magnet strengths. In calculating f_{max}, the beam width is assumed to be three times that of the RMS beam envelope width.

Regarding the placement of corrector magnets, it has been shown that the most efficient placement is with a 90 degree zero current phase advance between the elements of a corrector pair[1][3]. Also the effect of BPM errors is minimized when the BPMs are placed 90 degrees apart [3]. Figure 2 shows the phase vs. cell throughout the DTL (shown only for the empty cells)[2]. The zero current phase advance is relatively flat, indicating an almost constant

[1] This conclusion is for a scheme where the first BPM is located at the same position as the second corrector. In our case, all BPM locations are distinct from corrector locations.
[2] The jumps in phase at the tank entrances may be numerical artifacts (private communication, H. Takeda 7/00).

phase advance between available cells. This simplifies the choice of placement of corrector magnets and BPMs.

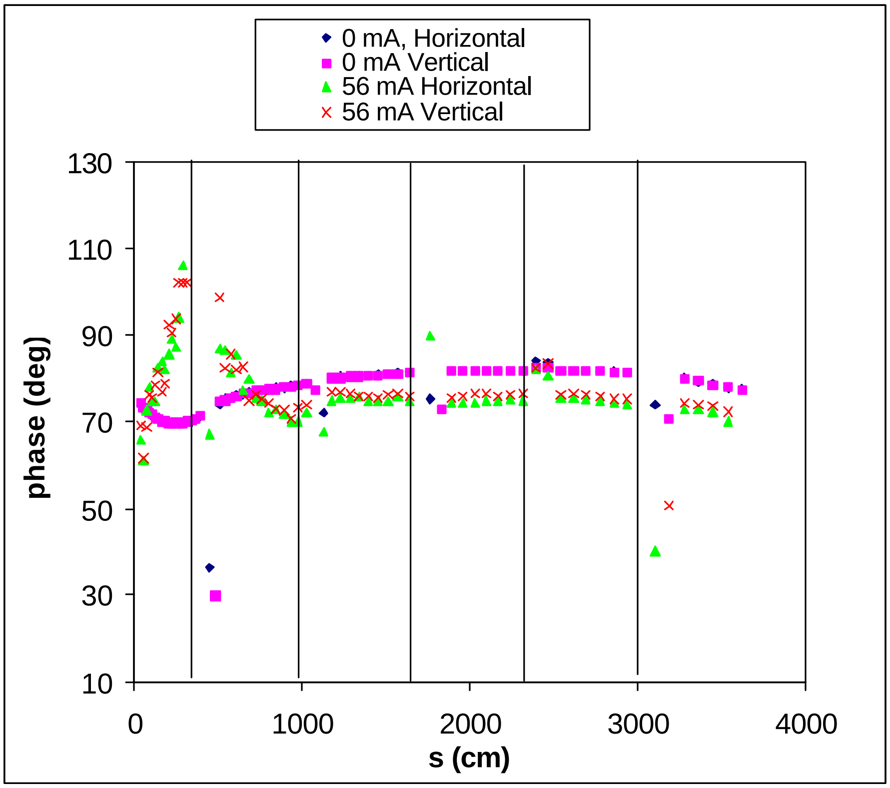
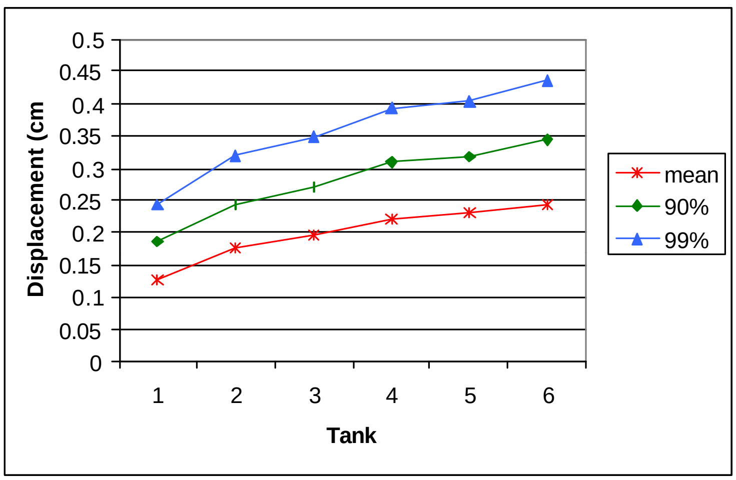


Figure 1. Phase advance vs. position along the DTL for zero current and the full current.

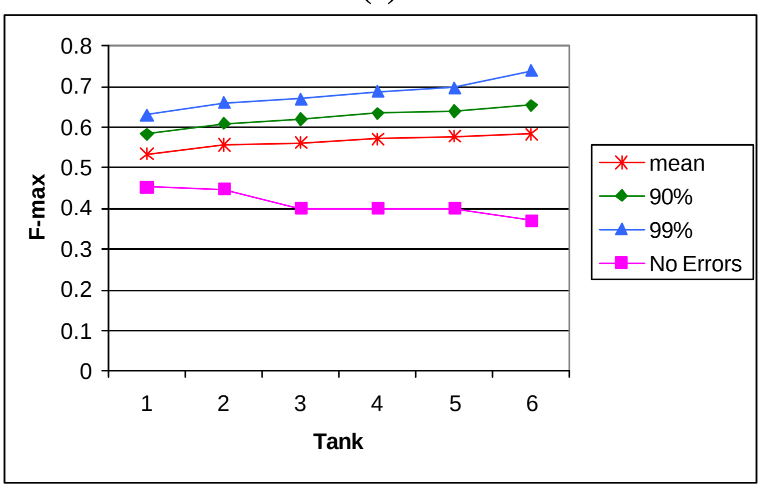
First we examine the impact of errors, with no correction. The magnitude of the beam displacement using the errors listed in Table 1 is shown in Figure 2a. Here the maximum displacement of the beam centroid within each tank is shown. Figure 2b shows the maximum fraction of the aperture occupied by beam, anywhere within each tank. Results are shown for different percentiles of the sampled cases. For example, the mean value for a particular tank represents the average of f_{max} for the 1000 cases run. The 90% f_{max} value represents the level for which only 10% of the cases were higher. It is seen that without correction, the presence of errors causes the beam to occupy a monotonically increasing fraction of the aperture. Also shown in Figure 2b is the f_{max} for the case with no errors. Without errors the beam monotonically decreases in size due to acceleration. Thus, the errors in the DTL can have a noticeable detrimental impact on the beam size. The average f_{max} is 25% higher with errors than without errors, at the end of the DTL.

Table 1. SNS DTL error specification. Only the errors listed in Italics are used in this study.

Type Error	**Tolerance limit (+)**
Quad transverse displacement	5.0 mil
Quad tilt	10 mrad
Quad roll	5.0 mrad
Quad gradient	0.25%
Segment to segment distance	10 mil
Gap to gap distance	2.0 mil
Segment transverse displacement	20 mil
Module field amplitude (dynamic)	0.5%
Module phase (dynamic)	0.9^o
Module field amplitude (static)	1.0 %
Module phase (static)	1.0^o
Segment field amplitude (static)	1.0 %
Module field amplitude tilt	1.0 %
BPM displacement	9 mil



(a)



(b)

Figure 2. (a) Beam displacement and (b) maximum fraction of the aperture occupied by beam, with no correction.

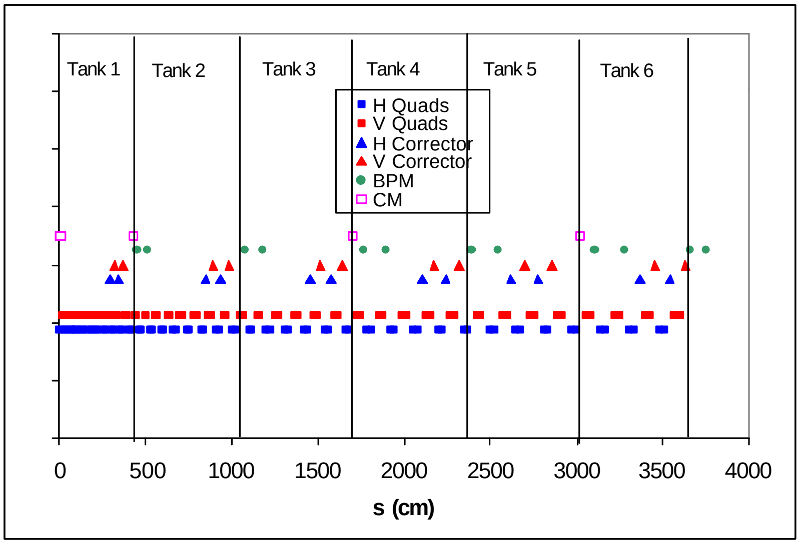
Corrector Pairs

As a first correction example we consider a single corrector pair set per transverse plane in each tank, followed by a single BPM set in the downstream tank. We place the corrects set members 6 cells apart (one focusing period). The first BPM is placed at the first available cells in the next downstream tank[3]. The fields in each corrector set are solved to return the beam to the axis at the downstream BPM set. Figure 3a schematically shows the locations of the quads, correctors, BPMs and tank boundaries. Using these positions, the maximum beam displacement is shown in Figure 4a. Also shown in Fig. 4b and 4c are the occupied fraction of the aperture (f_{max}) and the required corrector strengths. Use of correctors greatly improves the control of the beam. The average error case has and f_{max} only 10% higher than that of the no error case at the end of the DTL. Although the f_{max} level with this corrector scheme is still higher than for the case with no errors, the situation is greatly improved over the case with no correctors. The average corrector field is near 600 gauss-cm in the early tanks and falls to 400 gauss-cm for the later tanks. For the extreme error cases (< 1% likelihood), the correctors are pushed to 1400 gauss-cm. Several corrector pair location schemes were studied and the results were very similar to those shown in Fig. 4. This is likely due to the nearly constant phase per empty cell shown in Fig. 1.

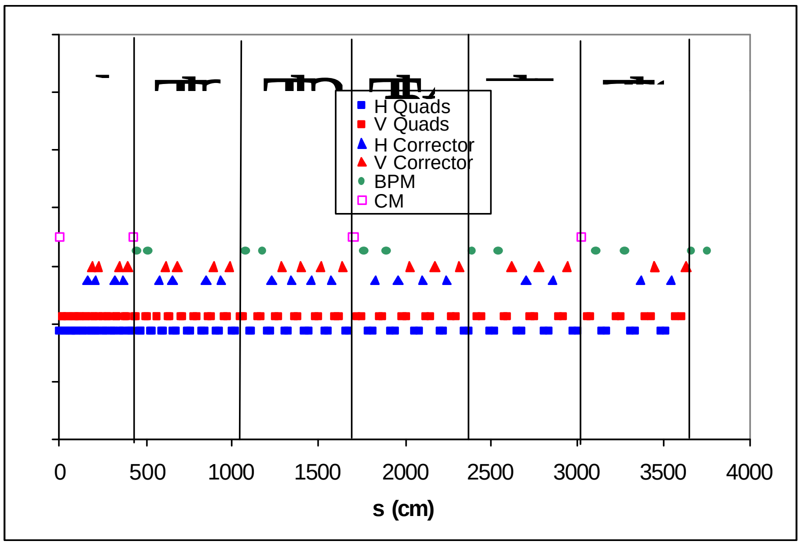
Multiple Correctors

Another corrector strategy is to use multiple correctors. In this case, several correctors are used to steer the beam on axis at two downstream BPM locations, while minimizing the sum of the squares of the corrector strengths. Figure 3b shows the corrector and BPM locations assumed for this study. We use up to 8 correctors per tank - most of the available empty cells are utilized here. Note that in tank 6, there are not enough empty cells to accommodate more than 2 corrector pairs, so for this tank the correction scheme is similar to that above. The displacement, f_{max} and steering strengths are shown in Fig. 5. The displacement and f_{max} levels are similar to those of the corrector pair case. But the corrector strengths are lower for tanks 1-4 (tanks 5 and 6 have similar numbers of correctors as in the above section).

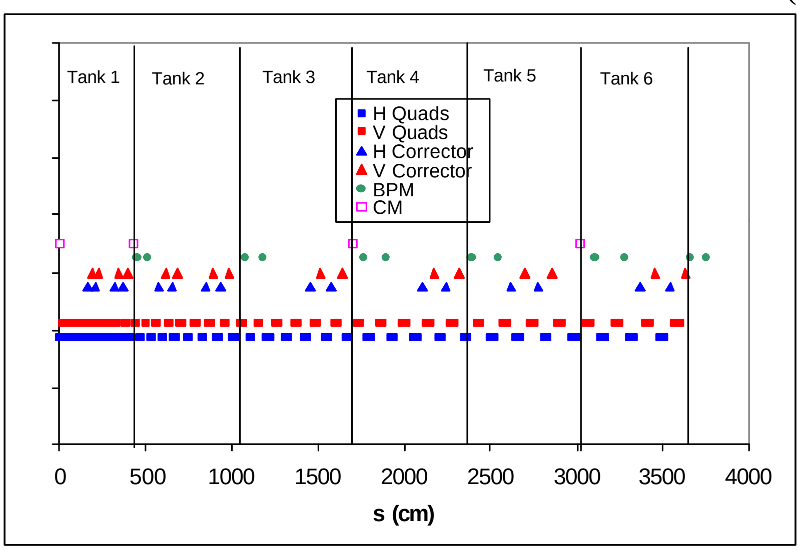
[3] After tank 6 one BPM is placed 5 cm after the end of tank6 (in the DTL/CCL transport section), and the second BPM is placed 5 cm downstream from the first CCL segment (before the inter segment quad).



(a) corrector pairs

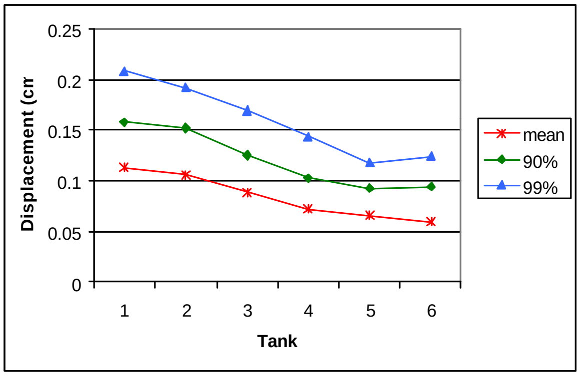


(b) multiple correctors



(c) combination multiple / pair correctors

Figure 3. Corrector magnet, BPM and current monitor locations in the DTL (BPMs are dual plane). (a) using a single corrector pair per plane per tank, (b) using multiple corrector pairs per tank, and (c) using multiple pairs in tanks 1 and 2 and corrector pairs in tanks 3-6.



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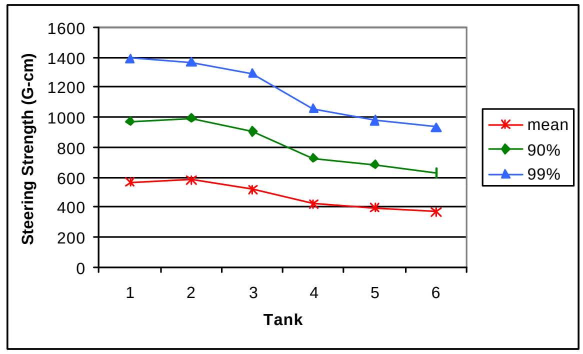

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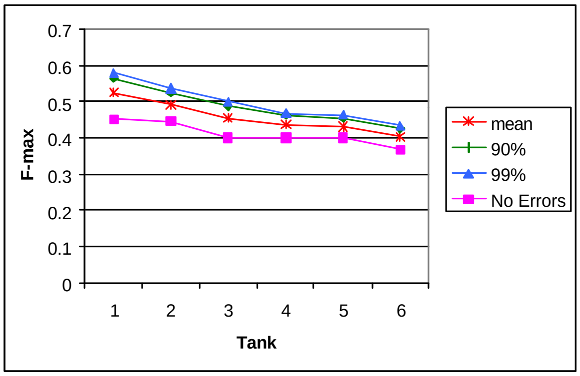


(b)

Figure 4. (a) Beam displacements and (b) maximum fractions of the aperture occupied by beam, and (c) corrector strengths with the pair corrector scheme.

Multiple / pair combo

Since the beam oscillation about the machine axis is proportional to the quad displacement magnitude and to $\sqrt{N_{quads}}$, the early tanks are more susceptible to beam displacement than the latter tanks (since they have more quad components). To address this vulnerability, we consider the case with multiple correctors in tanks1-2, and only single corrector pairs in tanks 3-5. The locations of the quads for this case are shown in Table 2 and the geometry is shown in Figure 3c. The corresponding maximum beam displacement, maximum fractions of the beam pipe occupied by beam and required correcting filed are shown in Fig. 6. For tanks 1-2, the results are the same as the multiple corrector case, and for tanks 3-6, the results are similar to those of the corrector pair case.

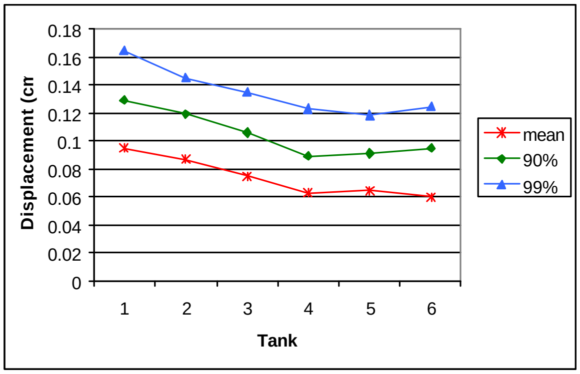
Error Sensitivity

As a test of the capability of the corrector system to larger error values, we assume twice the error levels shown in Table 1. Figure 7 shows the displacement, and corrector magnetic field levels for the corrector pair scheme with doubled error levels. The displacements and required corrector strengths are increased by about a factor of two with the doubling of the errors. The f_{max} levels are increased by roughly 10%. For tanks 1-3, the corrector magnets are at the 1700 gauss-cm limit for the top 10% of the worst error cases. This shows that using corrector pairs only results in a vulnerability of tanks 1-2 to higher than expected error levels.

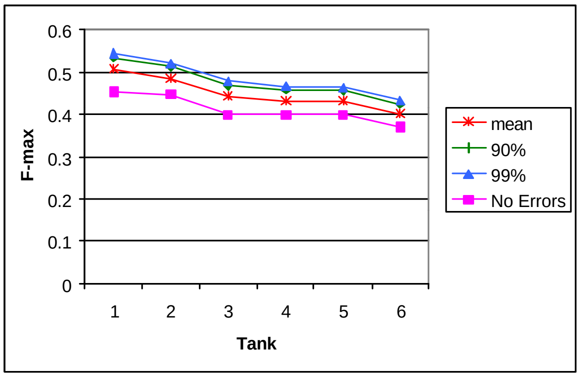
Figure 8 shows the doubled error results for the case with multiple correctors in tanks 1-2 and single corrector pairs in tanks 3-6. This case has better beam correction (i.e. smaller f_{max}) and lower corrector field strengths than the pair only case. The advantage of using multiple corrector magnets in tanks 1-2 is for the event that the errors are larger than assumed in Table 1, and to provide some redundancy in the tanks most susceptible to larger beam oscillations.

References

1 – K. Crandall, “Documentation for PARTREX”, unpublished,
2 – J. Stovall, E. Gray, S. Nath, H. Takeda, R. Wood, L. Young, K. Crandall, “Alignment and Steering Scenarios for the APT Linac”, proceedings LINAC 1998 ????, p. 686.
3 – K. Crandall, “Steering Considerations for the SNS Linac”, 9/30/99.



(a)



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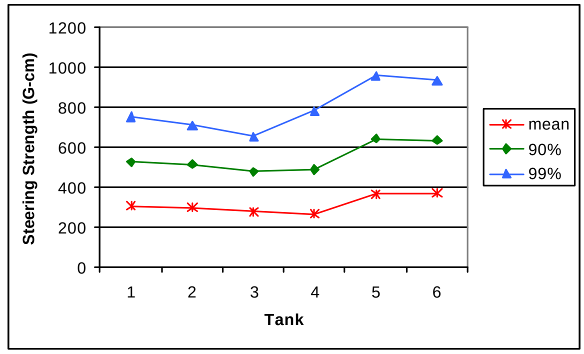
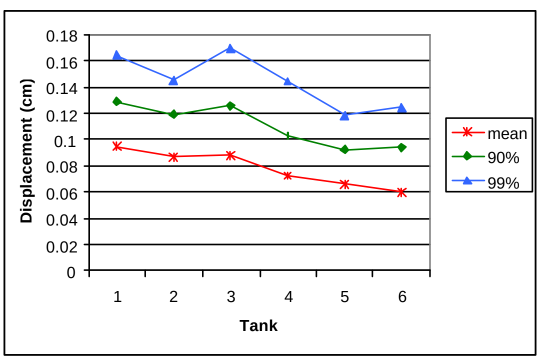


(c)

Figure 5. (a) Beam displacements and (b) maximum fractions of the aperture occupied by beam, and (c) corrector strengths with the multiple corrector scheme.



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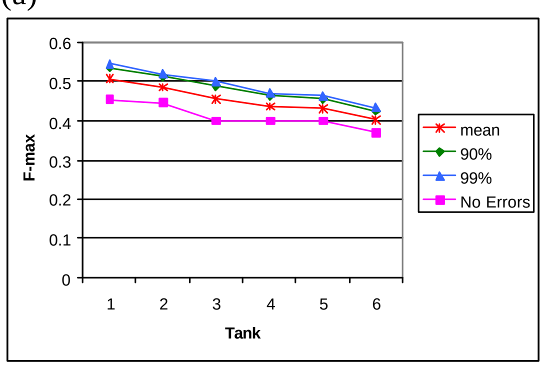

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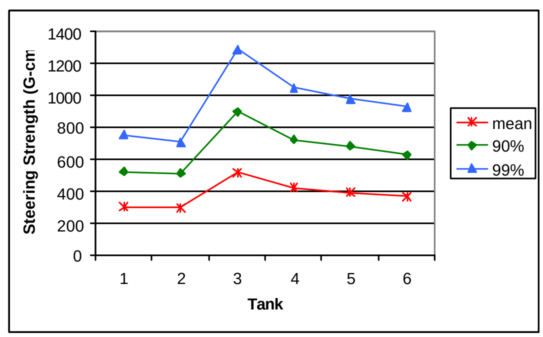
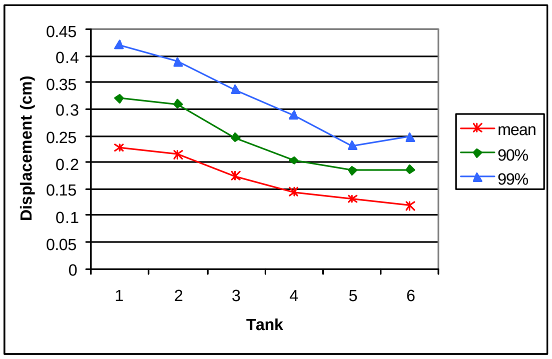


(c)

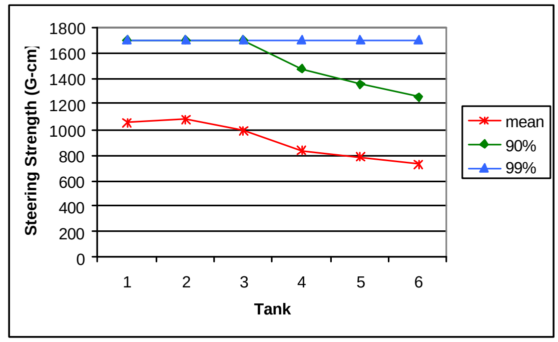
Figure 6. (a) Beam displacements and (b) maximum fractions of the aperture occupied by beam, and (c) corrector strengths with the combination multiple / pair corrector scheme.

Table 2. Positions of the correctors and BPMs for the combined pair-multiple scheme. The position listed is at the end of the specified cell. The cell numbers start at the beginning of the DTL tank 1.

Horizontal corrector			Vertical Corrector			BPM		
Tank	Cell	Pos. (cm)	Tank	Cell	Pos. (cm)	Tank	Cell	Pos. (cm)
1	28	165.8	1	31	185.728	2	63	453.226
1	34	206.3	1	37	227.4	2	69	514.02
1	49	318.996	1	52	343.94	3	110	1079.494
1	55	369.819	1	58	396.698	3	116	1180.686
2	75	579.535	2	78	614.119	4	145	1763.95
2	81	649.943	2	84	687.024	4	151	1894.97
2	96	848.24	2	99	891.845	5	171	2391.147
2	102	936.8	2	105	983.118	5	177	2542.64
3	131	1456.58	3	134	1515.62	6	197	3107.02
3	137	1575.94	3	140	1637.52	6	203	3276.77
4	160	2100.61	4	163	2171.54	DTL-CCL trans.		3662
4	166	2243.64	4	169	2316.91	DTL-CCL trans.		3752
5	180	2620.07	5	183	2698.62			
5	186	2778.26	5	189	2858.99			
6	206	3363.11	6	209	3450.57			
6	212	3538.53	6	215	3627.54			



(a)



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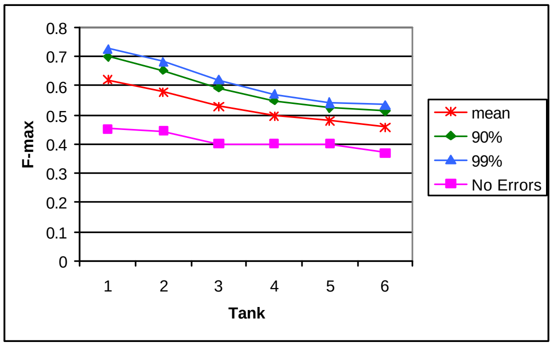
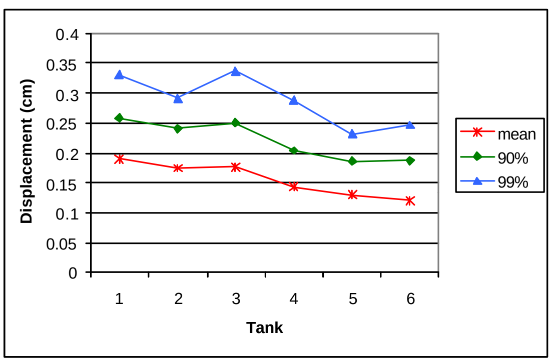
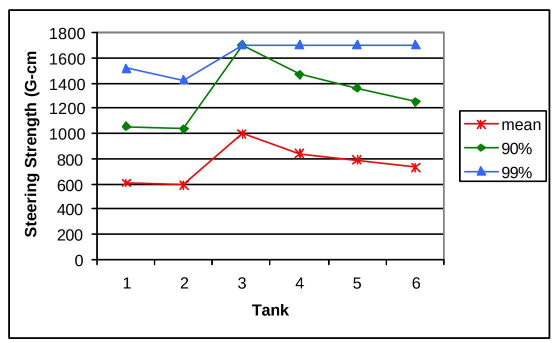


(b)

Figure 7. (a) Beam displacements and (b) maximum fractions of the aperture occupied by beam, and (c) corrector strengths with the pair corrector scheme with twice the nominal error level.



(a)



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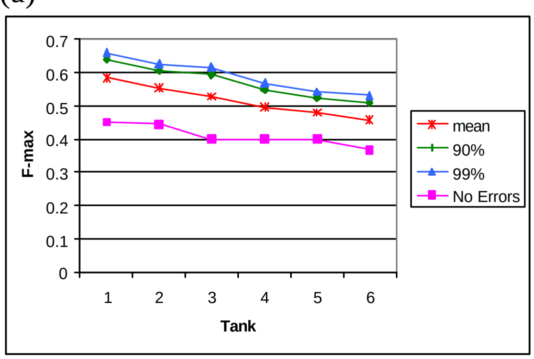

(b)

Figure 8. (a) Beam displacements and (b) maximum fractions of the aperture occupied by beam, and (c) corrector strengths with the combination multiple/pair corrector scheme with twice the nominal error level.